A major purpose of the Technical Information Center is to provide the broadest dissemination possible of information contained in DOE's Research and Development Reports to business, industry, the academic community, and federal, state and local governments.

Although a small portion of this report is not reproducible, it is being made available to expedite the availability of information on the research discussed herein.

1

LA-UR--84-808

DE84 010059

NOTICE

PORTIONS OF THIS REPORT ARE ILLEGIBLE. It has been reproduced from the best available copy to permit the broadest possible availability.

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36

CONF-8403118--1

TITLE: SOME PHYSICAL CONCEPTS IN COMPLEX TERRAIN METEOROLOGY DERIVED FROM THE U. S. DEPARTMENT OF ENERGY'S ASCOT PROGRAM

AUTHOR(S): W. E. Clements, ESS-7

SUBMITTED TO: Int'l Symp. on the Qinghai-Xizang (Tibet)
Plateau and Mountain Meteorology
March 20-24, 1984
Beijing, P.R.C.

Los Alamos

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

FORM NO. 836 R4

SOME PHYSICAL CONCEPTS IN COMPLEX TERRAIN METEOROLOGY DERIVED FROM THE U. S. DEPARTMENT OF ENERGY'S ASCOT PROGRAM

William E. Clements

Atmospheric Sciences Group
Earth and Space Sciences Division
Los Alamos National Laboratory
Los Alamos, New Mexico, USA 87545

March 1984

ABSTRACT

Since 1978 the United States Department of Energy's Atmospheric Studies in Complex Terrain program has conducted research fundamental to a better understanding of atmospheric transport and diffusion in complex topographies. Expertise in atmospheric physics theory, computer modeling, laboratory modeling, and field experimentation have been integrated into a balanced program. The initial emphases of the research were on nocturnal drainage winds, the effect terrain has on them, and their interactions with external flows. Highlights of some physical concepts of nocturnal drainage winds, derived mainly from the results of the field experiments, are presented.

1. INTRODUCTION

In 1978 the United States Department of Energy (DOE) initiated a program directed specifically at atmospheric studies in complex terrain (ASCOT). The two broad objectives of the ASCOT program are:

- To improve fundamental knowledge of atmospheric transport and dispersion processes in complex terrain.
- Building on this improvement in the understanding of the physics to provide a methodology for performing air quaility assessments.

These objectives are approached through an integrated program consisting of atmospheric physics theory, computer modeling, laboratory modeling, and field experimentation. The ASCOT team is composed of scientists from DOE-supported research laboratories, other federal laboratories, and universities. The accomplishments of the ASCOT program are the result of the combined efforts of many dedicated individuals. A complete list of participants is given by Gudiksen and Dickerson (1984). The initial emphases of the research are on nocturnal drainage winds, the effect terrain has on them, and their interactions with external flows. This paper describes some physical concepts of nocturnal drainage wind derived mainly from the results of the meteorological measurements portion of the field experiments.

Detailed descriptions of any part of the ASCOT program is not the intent of this overview paper. A comprehensive summary of all phases of the ASCOT program is given by Dickerson and Gudiksen (1984). Interested readers are encouraged to seek out this and all other references given in this paper for further information.

2. THE FIELD SITES

ASCOT has conducted intensive field studies at the five locations shown in Fig. 1. The topography of each of these sites is very different. The general characteristics of each site will be briefly described below in the order of their relative complexity. In each case references are given to more detailed descriptions of the sites and the experiments conducted.

RATTLESNAKE HILL: Located in the southeastern corner of the state of Washington, Rattlesnake Hill approximates a fairly uniform two-dimensional slope. It slopes from southwest at 595 m MSL to northeast at 366 m MSL for a distance of over 900 m. In the area of the hill where measurements were made there are two distinct angles to the slope. From the summit to about 495 m MSL the slope is 20° and below this point it is 8°. The average slope from the summit to the bottom is 16°. (Doran and Horst, 1983a,b; Horst and Doran, 1981, 1982)

PAJARITO MOUNTAIN: In 1979 and 1983 slope experiments were conducted on a fairly uniform ski run on Pajarito Mountain in the north central New Mexico. The ski run slopes from the south at 3090 m MSL to the north at 2830 m MSL for a distance of 850 m with an average slope angle of 18°. It is 50 m wide and is bordered on each side by dense stands of aspen and spruce approximately 15 m high. This site approximates a uniform two-dimensional slope. (Clements and Nappo, 1983)

CORRAL GULCH: Corral Gulch, located in northwestern Colorado, was the site of field studies in 1980 and 1981. The experimental site is a shallow valley 15 km long. It drains roughly from the west at 2940 m MSL to the east at 1950 m MSL with an average slope of about 4°. At the location where measurements were made it is 60 m deep, 600 m wide, and has a local slope of only 1°. The sidewalls are steep (20 to 30°) and cut regularly by small tributaries. (Clements et. al., 1981; Barr and Clements, 1981; Barr et. al., 1983)

BRUSH CREEK: Brush Creek, also located in northwestern Colorado, is a 600 m deep valley with sidewalls that average 30° and at some places are much steeper. The valley floor drains for 22 km from the northwest at 2440 m MSL to the southeast at 1380 m MSL. The average slope is 2°. At the mouth of the valley the floor is about 1 km wide and near the headwaters it is very narrow. The sidewalls are cut regularly by sizable tributaries. Experiments were conducted here in 1982 and another set is planned for the fall of 1984. (Gudiksen, 1984)

GEYSERS: The study site in the Geysers area of northern California is a complex basin. It consists of a number of significant valleys and many small tributaries. The major drainage in the basin is from the northwest to the southeast ending in a restricted outflow region. Ridges composing the rim of the basin range in altitude from about 980 m MSL to over 1400 m MSL. The altitude of the most restricted portion of the outflow region is 390 m MSL. The basin can be thought of as circular with a diameter of 6 to 7 km. ASCOT conducted field experiments in this basin in 1979 and 1980. In 1981 the experimental site was moved from the Geysers Basin to Big Sulfur Creek, which is just over the western ridges of the basin. In this valley, which slopes down from the southeast to the northwest, cooling tower plume experiments were conducted. (Gudiksen, 1980, 1982, 1983; Dickerson, 1980)

These five experimental sites fall into three general topographic classifications

- Isolated simple slopes

  Rattlesnake Hill
  Pajarito Mountain

- Complex valleys

  Corral Gulch
  Brush Creek

- Complex basins

  Geysers

A complex valley is one with irregular sidewalls cut by tributaries. The isolated simple slope sites are used to study "simple drainage flows", which are the fundamental elements of the more complicated flows. The complex valleys and basins provide the setting for studying the effects of the merging of drainage winds.

3. THE FIELD STUDIES

The field studies at the above sites generally consist of intensive experimental periods of three to four weeks. During these times as many nocturnal periods with weather conditions conducive to good drainage winds are investigated as possible. This ranges from 3 to 6 nights depending on conditions. The period of the nocturnal studies usually runs from presunset to postsunrise in order to include the transitions into and out of the drainage wind regime. The intensive periods are usually complemented by a more modest long-term data collection. This is required to determine seasonal trends and the representativeness of the intensive studies.

During the intensive experiments two general types of studies are used to investigate the nocturnal drainage wind and its interaction with terrain and external flows. These are meteorological measurements and atmospheric tracer studies. The general types of meteorological instrumentation used in a particular intensive field experiment might include any or all of the following:

- Instrumented towers
- Optical anemometers
- Mobile meteorological sensors
- Free balloon-borne sensors
- Tethered balloon-borne sensors
- Monostatic acoustic sounders
- Bistatic doppler acoustic sounders
- Optically tracked neutrally buoyant balloons
- Radar tracked tetroons

Atmospheric tracer systems that have been applied in intensive studies are:

- <u>BALLOONS:</u>

  Neutrally buoyant balloons
  Tetroons

  Detection systems:

  Optical theodolites
  Radar

- <u>PARTICLES:</u>

  Smoke
  Fluorescent particles

  Detection systems:

  Integrated surface samplers
  Sequential surface samplers
  Ground based lidar
  Airborne lidar

- <u>GASES:</u>

  Naturally occurring radon-222
  Sulfur hexafluoride
  Two perfluorocarbons (PMCH, C_7F_{14}; PDCH, C_8F_{16})
  Two heavy methanes ($^{13}CD_4$; $^{12}CD_4$)

  Detection systems:

  Integrated surface samplers
  Sequential surface samplers
  Balloon-borne samplers
  Instrumented aircraft

Again the reader is referred to Dickerson and Gudiksen (1984) for further details of the instrumentation used in and the experimental design of each experiment. This reference will lead to even more detailed references. In this paper, I will concentrate on some of the results obtained from the meteorological measurements effort.

4. CONDITIONS FOR GOOD DRAINAGE WINDS

In this section some conditions for "good" drainage winds are discussed. The term "good" used in connection with drainage winds indicates that there is a minimum effect on the drainage winds by ambient meteorological conditions. In these cases the drainage wind is relatively stable and its characteristics are well defined.

On a clear night the absence of insolation allows the earth's surface to cool by long wave radiation. This surface cooling in turn attempts to cool the air near the ground. If this process is successful, a buoyancy deficit is created in the layer of air near the ground with respect to the ambient air above. If this situation occurs on a sloping surface, a katabatic force is created and the layer will begin to move or "drain" downslope. This flow is retarded by frictional forces and adiabatic warming so that at some point a more-or-less steady state is reached. The resulting flow is referred to as the "nocturnal drainage wind" or, more often, simply the "drainage wind".

Once establised, the drainage wind is usually thought of as being decoupled from the ambient wind above. This is essentially correct if the ambient conditions are constant. However, the development and characteristics of a particular drainage wind depend strongly on the ambient conditions in which it was formed. Futhermore, changes in the ambient conditions usually will modify the drainage wind. For instance, as will be discussed later, intrusions of strong upper level winds during the night may completely destroy it. Also, a change in cloud cover will alter the radiative balance at the surface and, hence, change the characteristics of the drainage layer. I have observed nights that begin with a heavy cloud cover and no drainage wind. Later on the cloud cover will pass and the drainage wind will start soon afterwards.

Data from a number of ASCOT studies indicate some general conditions for good drainage winds to occur. First, radiative cooling at the ground must occur. This can be prevented or impeded, as discussed above, by cloud cover. Next, the layer of air near the ground must cool to produce a buoyancy deficit and, hence a downslope or katabatic force. Strong ambient winds at the surface can advect away any cooling of the surface air. Also, high humidity will impede the cooling of the layer compared to relatively dry air.

On simple isolated slopes a surface inversion of a few C° in a few tens of meters or less is usually sufficient to initiate drainage winds. These are subject to interruption by moderate ambient winds due to lack of shelter. In more complex situations, such as in valleys and basins, where the drainage wind is the result of the convergence of a number of drainage flows, the surface inversion may be a few C° in a few hundred meters. In the latter cases it is not at all clear that the observed inversions provide the total driving force for the the flow or that it is simply being advected by the flow. A bulk slope Richardson number, Ri_B, proved to be a good indicator of drainage wind on a slope in the Geysers area. Horst and Doran (based on some earlier work; Horst and Doran, 1981) define the bulk slope Richardson number as

$$Ri_B = \frac{\Delta T}{U^2} \cdot \frac{gh}{T} \qquad (1)$$

where ΔT is the strength of the surface inversion of depth h, U and T are the wind speed and absolute temperature of the ambient air (at ridge top in the case of the Geysers study), and g is the gravitational acceleration.

Figure 2 shows the fraction of hours with good, fair and no drainage winds. These results, which at present have only been evaluated at the Geysers site, show that no drainage winds occur for $Ri_B < 0.15$, good slope flow never occurred for $Ri_B < 0.2$, and that most of the good slope flow was observed for $Ri_B > 0.7$. Horst and Doran (see Chapter 3: Physical Concepts in Dickerson and Gudiksen, 1984) point out that Ri_B is a diagnostic rather than a prognostic indicator, because of its dependence on the strength and depth of the surface inversion.

In summary, go ' drainage flows occur on nights when there are few to no clouds, the ambient winds are light to calm, and the air is relatively dry. Drainage winds of varying quality occur in a wide variety of ambient conditions and sometimes under surprisingly severe situations. A great many .actors are involved in the development of drainage winds in valleys and basins where they are sheltered. We are just beginning to understand some of these more complicated scenarios.

5. SOME GENERALIZED DRAINAGE WIND CHARACTERISTICS

The results of all the field studies show some characteristics of good drainage winds that appear to be independent of the complexity of the terrain. These features are useful in distinguishing drainage winds from synoptic winds that are channeled down a slope.

Before describing these characterisitics it is necessary to say something about the "depth" of a drainage wind. As discussed earlier established drainage flows are to a large extent decoupled from the ambient air above them. The distance from the ground up to the transition from drainage flow to ambient flow is a general definition for the depth. Although this sounds simple enough, the determination of the transition height is sometimes difficult and ambiguous. Changes in the vertical structure of temperature, wind direction, wind speed, and turbulent mixing are all used in attempts to define the depth of drainage winds. Horst and Doran (1981), King (1981), and Wolfsberg and Clements (1983) discuss the relative merits of these methods. It will suffice for the following discussions to accept that drainage winds exist over some finite depth near the ground.

Figure 3 shows the generalized vertical profiles of temperature, wind direction, and wind speed in and above a drainage wind layer of depth h. The following generalizations about these profiles can be made:

<u>TEMPERATURE:</u> The temperature increases from the surface upwards, approaching an isothermal state at the top of the layer. The temperature profile above the layer is most often isothermal.

<u>WIND DIRECTION:</u> The wind direction is downslope or downvalley in the drainage layer. Except in the frustrating cases when the ambient wind direction is downslope, there is a rather abrupt change in wind direction near the top of the layer. The wind direction immediatley above the drainage layer may be that of the synoptic wind or of an intermediate wind layer. The region between the top of the drainage layer and the synoptic wind is called the transition layer. The transition layer may be very simple as shown in Fig. 3. or extremely complex.

WIND SPEED: The wind speed profile within the drainage layer is characterized by a low-level jet with a wind speed minimum near the top of the layer. The maximum wind speed in the layer occurs at about half the layer depth or less. The wind speed above the layer can be zero when there are no ambient winds, increase to the ambient wind speed, or show secondary jets in the case of layered flow.

In addition to these features the turbulent structure in the drainage layer is characteristically different from the ambient wind. Clements and Nappo (1983) observed the range of the variation in wind direction to change from about 60 degrees prior to the development of a drainage wind on a simple slope to less than 10 degrees after drainage began. There is limited data on the vertical structure of turbulence in drainage winds. However it is expected to be quite different from that in the stable boundary layer over flat terrain. This is because of the different veritcal shear structure in the two cases. The vertical variation of turbulent energy production in slope flow is complex; however, the observed turbulence structure is generally consistent with local shear production of turbulence. (See Physical Concepts Chapter in Dickerson and Gudiksen, 1984).

Although the generalized characteristics given above are found in most drainage flows, the values of the parameters associated with them vary widely from site to site. In addition, as mentioned at the outset, the depth of a drainage wind may take on different values depending on which parameter is used for the determination. In the next section specific examples of these generalizations will be given and the discrepancies will be obvious.

6. SPECIFIC EXAMPLES OF DRAINAGE WIND CHARACTERISTICS

In this section examples of vertical profile data in drainage flows at each of the experimental sites are given and discussed. These examples have been chosen from good drainage flow situations; that is those cases wherein the drainage flow is steady and there is a minimum of influence from the ambient winds. The ASCOT data contain many examples that are not as clear cut as the ones presented here, which serve to remind us of how much we still have to learn about these phenomena.

RATTLESNAKE HILL: Figure 4 shows the vertical profiles of potential temperature and downslope wind speed at three towers on Rattlesnake Hill (a simple slope) from Doran and Horst (1983a). The towers are located at 193, 422, and 898 m along the slope (16^{o} average) from the crest. The depth of the inversion and the maximum downslope wind speed both increase with downslope distance. These profiles also indicate that the depth of the drainage layer is increasing with downslope distance.

PAJARITO MOUNTAIN: Another example of drainage layer growth on a simple slope comes from data collected on Pajarito Mountain. In this data both temporal and spatial growth of the drainage layer can be seen. Figures 5 and 6 show hourly average profiles of wind speed, wind direction, and temperature for three hours at two locations on the slope. This data was collected from two towers located at 285 and 820 m along the 18° slope from the crest. At the upper tower in the three hours shown the inversion strength increases with time. The depth of the downslope wind direction increases from very shallow to about 7 m in the three hour period. The maximum wind speed in the layer increases from the first to the second hour and then remains constant. At the lower tower the same type of trends are seen, but over greater depths. The final depth of the drainage wind in the last hour is in excess of 21 meters, which is the height of the highest instrument. Notice that the velocity maximum at both locations is considerably less than half the depth of the drainage flow.

CORRAL GULCH: Moving on to the first of our complex valleys, Corral Gulch, deeper drainage flows are found. Vertical profile data, including the mixing ratio, at this site obtained with a tethersonde are shown in Fig. 7. Here the top of the inversion, the point of wind direction shift, and the wind speed minimum all occur at about 200 m above the ground. During the four nights studied at this site, the depth of the drainage layer varied between 100 and 200 m. The wind speed maximum occurs at or slightly below the midpoint of the layer and averages between 2.0 and 2.5 m/s. The maximum shown in Fig. 7 is somewhat higher than average. There is a discontinuity in the mixing ratio somewhat lower than the top of the inversion. The fact that the mixing ratio is less in the drainage layer than above it is opposite to what is found at other sites and still remains somewhat of a mystery.

A much more subtle but persistent feature of the nocturnal flow is observed in this valley, which is not apparent in Fig. 7 (Barr and Clements, 1981). This is a weak down-valley windspeed maximum of about 1 m/s at roughly 10 m above the ground. This rather weak sublayer is easily obscured by stronger winds above.

A third layer with a wind speed maximum of 10 to 20 m/s at 500 m above the ground is described by Barr and Clements (1981). This layer is detected in pibal-minisonde profiles taken on open terrain about 7 km west of and 300 m above the tethersonde site. On two nights the flow in this layer is from the east when there is no evidence in the synoptic data for an easterly wind in the region. This layer appears to be due to a local topographic effect.

<u>BRUSH CREEK</u>: Figure 8 is vertical profile data taken in Brush Creek. Here potential temperature is plotted in place of the normal temperature. The wind speed profile shows the drainage layer jet with a well defined minimum at about 350 m. This is a little over half the depth of the valley. The maximum wind speed in the drainage layer is 7-8 m/s at about one-third the depth. This is typical of the Brush Creek drainage wind in summer. The only good indicator of the dainage depth in this case is the wind speed minimum above the jet.

Measurements made in Brush Creek in 1982 (Gudiksen, 1984) show an increase in the depth above the ground of the drainage layer with down-valley distance. There is some evidence that the top of the drainage layer is horizontal. This is consistent with the findings of Manins and Sawford (1979) who point out the analogy with a flooded internal jump.

GEYSERS: The last example is that of the drainage wind in the outflow region of the Geysers Basin. The vertical profile data, shown in Fig. 9, are somewhat atypical in the sense that this was not a particularly good drainage night. However, in spite of the lack of good drainage throughout the basin, there is a well defined drainage in the outflow region. This is most likely the result of very shallow, perhaps below most instrument levels, drainage flows converging from throughout the basin. The outflow drainage layer depth is a little over 100 m. There is a well defined temperature inversion, low-level jet, and wind direction discontinuity. The mixing ratio is higher in the drainage layer than above it, as would be expected of a trapping process like the stable drainage layer. The more interesting feature of this data is the 100 m or so southerly jet above the northwest drainage flow. This is overlain by northwest to north winds above 300 m. The southerly jet could possibly be a return flow to the basin. This is a good example of the type of layered flow that can exists in complex topography.

Throughout the basin the slope and valley drainage flows grow with downslope distance from ridgetop to the "pooling region", which is discussed in section 8. Upon approaching the pooling region, which is growing in depth with time, the growth of the drainage winds decrease and they soon become part of the pooling flow.

For the isolated simple slope cases a relationship for the depth of the drainage layer, h, is given by Briggs (1981) as

$$h = 0.038 \cdot s \cdot (\sin \beta)^{2/3} \qquad (2)$$

In equation (2) s is the distance along the slope from the crest and β is the slope angle. Data from Rattlesnake Hill and Pajarito Mountain generally verify this relationship.

Only a few examples of good drainage flow data have been given. The data from the ASCOT studies contain an enormous amount of information about nocturnal drainage winds and other related phenomena. Additional analyses have been and are continuing in parallel with the ongoing field studies.

7. INTERACTIONS WITH EXTERNAL FLOWS

Locally driven wind fields, such as dainage winds, seldom occur in nature as isolated features. There is almost always some interaction with the ambient meteorological conditions. At the Geysers there are three dominant larger-scale wind fields that affect the drainage flow.

These are: winds from migratory synoptic disturbances, seasonal sea breezes, and descending upper-level easterly winds.

At Geysers, the wintertime migratory synoptic features have an overriding influence on the drainage winds. In summer, when migratory storms occur less often, drainage winds are more persistent. In July and August good drainage winds occur on over 50 percent of the nights, while in January and February, they are present on less than 10 percent of the nights.

Very subtle features of the synoptic meteorological structure, such as the direction of a weak gradient flow, can influence the local drainage wind system. An easterly component over the Geysers area produces warming on the middle to upper slopes, destroys the drainage on the middle slopes, and gradually erodes the drainage flows at lower elevations. Figure 10 shows the gradual intrusion of northeasterly winds into the basin. This observed behavior is consistent with the systematic change in the wavelength of a nonlinear lee wave. If the wavelength is close to that of the lateral dimensions of the hill, the flow will tend to follow the topography. If the wavelength is significantly different, separation will occur. A relationship developed by Hunt et al. (1978) for hills of moderate slope and for a narrow range of wavelengths, which was tested with the Geysers data, was found to give a general indication of when intrusions of upper level winds occur. The condition for for the ambient wind to follow the terrain is given by

$$2L \leq \Lambda < 5L \tag{3}$$

where Λ is the wavelength and L is the half width of the hill at half-height. The wavelength is given by

$$\Lambda = \frac{2\pi U}{N} \tag{4}$$

where U is the ambient wind speed, N is the Brunt-Vaisala frequency,

$$N = \left[\frac{g}{\theta} \cdot \frac{\partial \theta}{\partial z} \right]^{1/2}, \tag{5}$$

and θ is the potential temperature. The Geysers geometry is more complex than that considered by Hunt et al. (1978) so equation (3) offers only a broad guideline.

The invasion of Geysers by marine air is related to the coastal sub-tropical high pressure area and inland thermal low pressure area. A diurnal oscillation in the marine air is partly due to a similar oscillation in the coastal-inland horizontal pressure gradient ($P_{coast} - P_{inland}$). An increase in this gradient coincides with a decrease in the marine air influx and the beginning of the nocturnal drainage regime. The magnitude of the sea breeze influence is linked to synoptic scale structure.

some subtle. We have just begun to understand the importance of these interactions and some of the mechanisms by which they occur.

8. LAYERING AND POOLING AT GEYSERS

In the Geysers are some interesting nocturnal flow phenomenon resulting wo topographic features of the basin. These are intersecting valleys within the basin and the restricted outflow region.

The nocturnal outflow from the Geysers Basin is mostly the result of the confluence of drainage flows from four major valleys. The flow in each valley being composed of drainage winds from its headwaters near ridgetop and inflows from its sidewalls and tributaries. Each of the valleys has its own drainage flow characteristics defined by its physical structure and orientation within the basin. Measurements made near the confluence of two or more valleys may vary unexpectedly due to an oscillating influence from each valley (Coulter, 1981). Because the flows from the different valleys may have different density structures, stratification may occur. This can produce layered flow in the convergence zones of the valleys and subsequently in the outflow region. Acoustic sounder records located in these areas show many instances of multilayered structure in the lowest 500 m. A different type of layering in the outflow region is shown in the data of Fig. 9. Here the layer above the drainage flow is almost in the opposite direction. This may be a case of a return flow to the basin above the drainage layer. The interaction of these stratified layers with the outer flow often generates gravity waves and instabilities at the layer interfaces. These contribute to the transition layer dynamics.

The outflow region of the Geysers is less than 1 km wide. The basin dimensions are 6 to 7 km. On nights with good drainage flow throughout the basin drainage air is produced faster than it can flow out of the basin. This results in a pooling region upstream of the basin exit. The horizontal and vertical extent of the pooling region is a function of the strength of the drainage winds throughout the basin. This convergence in the pooling region manifests itself in the form of a vertical velocity reduction. That is, the negative vertical velocity associated with the drainage winds is reduced in magnitude and may become positive in the pooling region. Assuming incompressible flow, the change in the vertical velocity with height can be related to the horizontal convergence through the continuity equation

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \qquad (6)$$

The depth through which the convergence occurs is also required.

The depth of the pooling region and a convergence parameter were estimated for the 1980 Geysers experiments from potential temperature patters derived from tethersonde profiles and doppler acoustic profile data. The convergence parameter is defined as

$$\text{Convergence Parameter} = \frac{\partial w}{\partial z} \qquad (7)$$

The depth of the pooling region ranges from 120 to 250 m. The shallower depths occur, as expected, on nights with the weakest drainage flow. Values of the convergence parameter are between 0.0 and 0.001 s^{-1}; the smaller values occurring on nights with weak drainage winds. The pooling of the drainage air near the outflow of the basin is an interesting phenomenon that needs further investigation.

9. RADON AS AN INDICATOR OF DRAINAGE WINDS AT GEYSERS

Naturally occurring radon 222 was measured continuously 1 m above the ground in the outflow of the Geysers Basin during the 1980 study (Clements and Wilkening, 1981). Radon 222, an inert radioactive gas with a half-life of 3.8 days, can be considered in this application to be exhaled uniformly at a constant rate from the earth's surface throughout the basin. As cool slope winds move along the terrain and into the valley, the air masses involved accumulate radon through the night until morning instabilities mix it to greater depths. The diurnal trend of the near-surface radon in the outflow of the basin reflects the intergrated drainage flow conditions throughout the night, the morning and evening transition periods, daytime vertical mixing, and the influence of strong synoptic winds on the drainage flow.

On nights when good drainage flow occurred the diurnal trend in radon concentration reveals a characteristic pattern shown in Fig. 11. Low radon concentrations exists during the day followed by a sharp increase beginning just before sunset and continuing for about 2 hours. This period was typically followed by a gradual increase during the night. A sharp drop is observed after sunrise when surface heating and the resulting vertical mixing occur.

Departures for this standard pattern observed on nights when the external flow had a greater influence include: (1) almost no build up at night over daytime levels, (2) delayed build up occurring during the evening hours when unsettled conditions prevail, and (3) radon concentration decreases during some periods due to destabilization events or intrusion of the ambient winds.

10. SUMMARY

I have tried to give an overview of the United States Department of Energy's ASCOT program and touch upon some of the physical concepts derived mostly from the experimental phase of the reseach. Equally essential and interesting research is being conducted in the areas of atmospheric physics theory, computer modeling, laboratory experiments, and field tracer experiments. It is unfortunate that due to the diversity of the ASCOT program these other phases of the research could not be discussed in this paper. I encourage the interested reader to seek out the overview references given.

Since its beginning in 1978, the ASCOT program has strived to improve our understanding of the fundamental physical processes of complex terrain meteorology. It is hoped that this will provide a better basis for making air quality assessments in areas of nonuniform topography. Several terrain settings have been investigated in order to build a broad base of knowledge that at some point, hopefully, can begin to be generalized in a consistent theory. These studies have made it clear that the problem of transport and diffusion in complex terrain is complicated and that interactions on all scales are important. Only through the cooperation of all those concerned with complex terrain meteorology will we ever hope to reach a definitive understanding of these important problems.

ACKNOWLEDGMENTS

The ASCOT program is a team effort and every participant shares in any credit for its success. For this paper I am particularly indebted to Sumner Barr, Rich Coulter, Chris Doran, Paul Gudiksen, Tom Horst, Carmen Nappo, Monte Orgill, Bill Porch, and Marvin Wilkening. These individuals made major contributions to the sections of the Physical Concepts chapter of the ASCOT Technical Progress Report for 1979 through 1983 on which most of this paper is based. In fact, in places they will undoubtedly recognize close approximations to their own words. I greatly appreciate the support of this effort by Marv Dickerson (ASCOT Scientific Director) and Dave Ballantine (ASCOT Program Manager, DOE/OHER). I also thank John Archuleta, Don Hoard, and Sue Noel for helping with the illustrations. This work was performed under the auspices of the United States Department of Energy.

REFERENCES

Barr, S. and W. E. Clements, 1981: Nocturnal wind characteristics in high terrain of the Piceance Basin. Preprints Second Conference on Mountain Meteorology, November 9-12, 1981, Steamboat Springs, Colorado, American Meteorological Society, 325-330.

Barr, S., T. G. Kyle, W. E. Clements, and W. Sedlacek, 1983: Plume dispersion in a nocturnal drainage wind. Atmos. Environ., 17, 1423-1429.

Clements, W. E. and M. Wilkening, 1981: Dirunal radon-222 concentrations in the outflow of a complex basin. Preprints Second Conference on Mountain Meteorology, November 9-12, 1981, Steamboat Springs, Colorado, American Meteorology Society, 212-217.

Clements, W. E. and C. J. Nappo 1983, Observations of a drainage wind event on a high-altitude simple slope. J. Cli. and Appl. Meteor., 22, 331-335.

Clements, W. E., S. Goff, J. A. Archuleta, and S. Barr, 1981: Experimental design and data of the August 1980 Corral Gulch nocturnal wind experiment, Piceance Basin, northwestern Colorado. Report LA-8895-MS, Los Alamos National Laboratory, Los Alamos, New Mexico, 197 pp.

Coulter, R. L., 1981: Circulation characteristics during ASCOT 1980. Preprints Second Conference on Mountain Meteorology, November 9-12, Steamboat Springs, Colorado, American Meteorological Society, 316-320.

Dickerson, M. H. (editor), 1980: A collection of papers based on drainage wind studies in the Geysers area of northern California: Part I. Report: ASCOT-80-7, Lawrence Livermore National Laboratory, Livermore, California.

Dickerson, M. H. and P. H. Gudiksen (editors), 1984: Atmospheric studies in complex terrain, technical progress report, FY-1979 through FY-1983. Report: ASCOT-84-1, Lawrence Livermore National Laboratory, Livermore, California.

Doran, J. C. and T. W. Horst, 1983a: Observations of drainage winds on a simple slope. Preprints Sixth Symposium on Turbulence and Diffusion, March 22-25, 1983, Boston, American Meteorological Society, 166-168.

Doran, J. C. and T. W. Horst, 1983b: Observations and models of simple nocturnal slope flows. J. Atmos. Sci., 40, 708-717.

Gudiksen, P. H. and M. H. Dickerson (editors), 1984: Executive summary: atmospheric studies in complex terrain, technical progress report, FY-1979 through Fy-1983. Report: ASCOT-84-2, Lawrence Livermore National Laboratory, Livermore, California.

Gudiksen, P. H. (editor), 1980: ASCOT data from the 1979 field measurement program in Anderson Creek, California. Report: ASCOT-80-9, Lawrence Livermore National Laboratory, Livermore, California.

Gudiksen, P. H. (editor), 1982: ASCOT data from the 1981 cooling tower plume experiments in the Geysers geothermal area. Report: ASCOT-82-4, Vols. I and II, Lawrence Livermore National Laboratory, Livermore, California.

Gudiksen, P. H. (editor), 1983: ASCOT data from the 1980 field measurement program in the Anderson Creek Valley, California. Report: ASCOT-83-1, Vols. I, II, and III, Lawrence Livermore National Laboratory, Livermore, California.

Gudiksen, P. H. (editor), 1984: ASCOT data from the 1982 field measurement program in western colorado. Report: ASCOT (in press), Lawrence Livermore National Laboratory, Livermore, California.

Horst T. W. and J. C. Doran, 1981: Observations of the structure and development of nocturnal slope winds. Preprints Second Conference on Mountain Meteorology, November 9-12, 1981, Steamboat Springs, Colorado, American Meteorological Society, 201-205.

Horst T. W. and J. C. Doran, 1982: Simple nocturnal slope flow data from the Rattlesnake Mountain site. Report: PNL-4406/ASCOT-82-5, Pacific Northwest Laboratory, Richland, Washington, 98 pp.

Hunt, J. C. R., W. H. Snyder, and R. E. Lawson, Jr., 1978: Flow structure and turbulent diffusion around a three-dimensional hill. Environmental Protection Agengy report: EPA-600/4-78-041, 84 pp.

King, C. W., 1981: Nocturnal drainage flow studies in complex terrain using an acoustic sounder and tethersonde. Preprints Second Conference on Mountain Meteorology, November 9-12, 1981, Steamboat Springs, Colorado, American Meteorological Society, 193-200.

Manins, P. C. and B. L. Sawford, 1979: A model of katabatic winds. J. Atmos. Sci., 36, 619-630.

Wolfsberg, D. and W. E. Clements, 1983: On determining depths of drainage winds. Preprints Sixth Symposium on Turbulence and Diffusion, March 22-25, 1983, Boston, American Meteorological Society, 121-122.

FIGURE CAPTIONS

Fig. 1. Locations of ASCOT experimental sites.

Fig. 2. Dependence of drainage wind on the bulk slope Richardson number, Ri_B, for a slope site in the Geysers Basin.

Fig. 3. Generalized vertical profiles of temperature, wind direction, and wind speed in an idealized drainage wind of depth h.

Fig. 4. Profiles of potential temperature (top) and downslope wind speed (bottom) at towers A, B, and C on Rattlesnake Hill. Tower A is nearest the top of the ridge and C is nearest the bottom. From Doran and Horst (1983).

Fig. 5. Hourly average profiles of wind speed, wind direction, and temperature at the upper tower on Pajarito Mountain. Times shown in the upper right hand corner of each plot are mountain standard time on November 6, 1983.

Fig. 6. Hourly average profiles of wind speed, wind direction, and temperature at the lower tower on Pajarito Mountain. Times shown in the upper right hand corner of each plot are mountain standard time on November 6, 1983.

Fig. 7. Tethersonde profiles of temperature (T), wind direction (WD), wind speed (WS), and mixing ratio (MR) in Corral Gulch.

Fig. 8. Tethersonde profiles of wind direction (W.D.), wind speed (W.S.), mixing ratio (M.R.), and potential temperature in Brush Creek.

Fig. 9. Tethersonde profiles of temperature (T), wind direction (WD), wind speed (WS), and mixing ratio (MR) in the outflow region of the Geysers Basin.

Fig. 10. Cross section parallel to the external wind direction showing the gradual incursion of NE winds into the Geysers Basin on September 22, 1980. The lines showing the level of the beginning of the NW winds are labeled with pacific standard time.

Fig. 11. Generalized diurnal pattern of radon 222 concentration in the Geysers outflow region for good nocturnal drainage conditions. From Clements and Wilkening (1981).

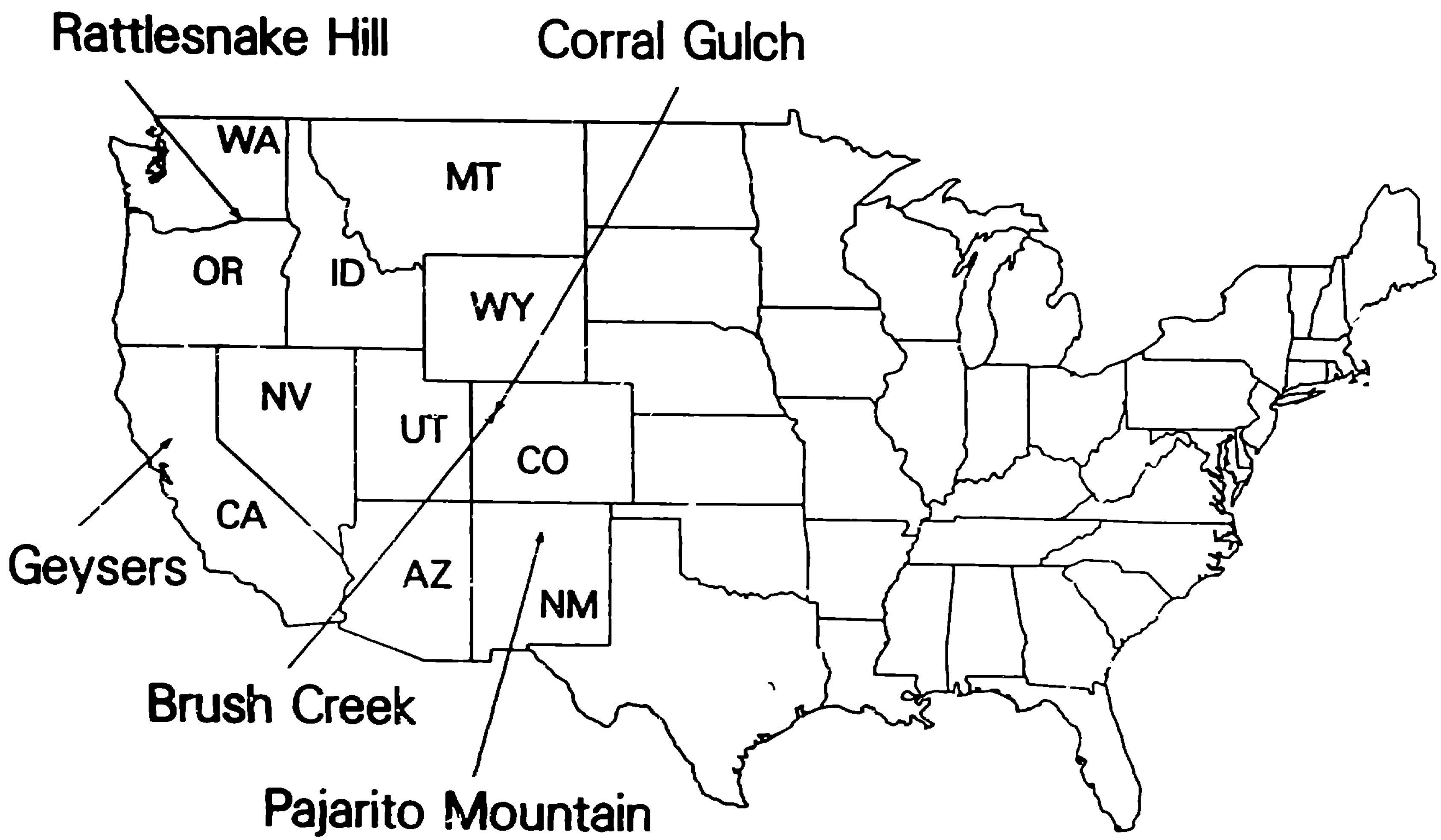

Rattlesnake Hill
Corral Gulch
WA
MT
OR
ID
WY
NV
UT
CO
CA
AZ
NM
Geysers
Brush Creek
Pajarito Mountain

FIG. 1

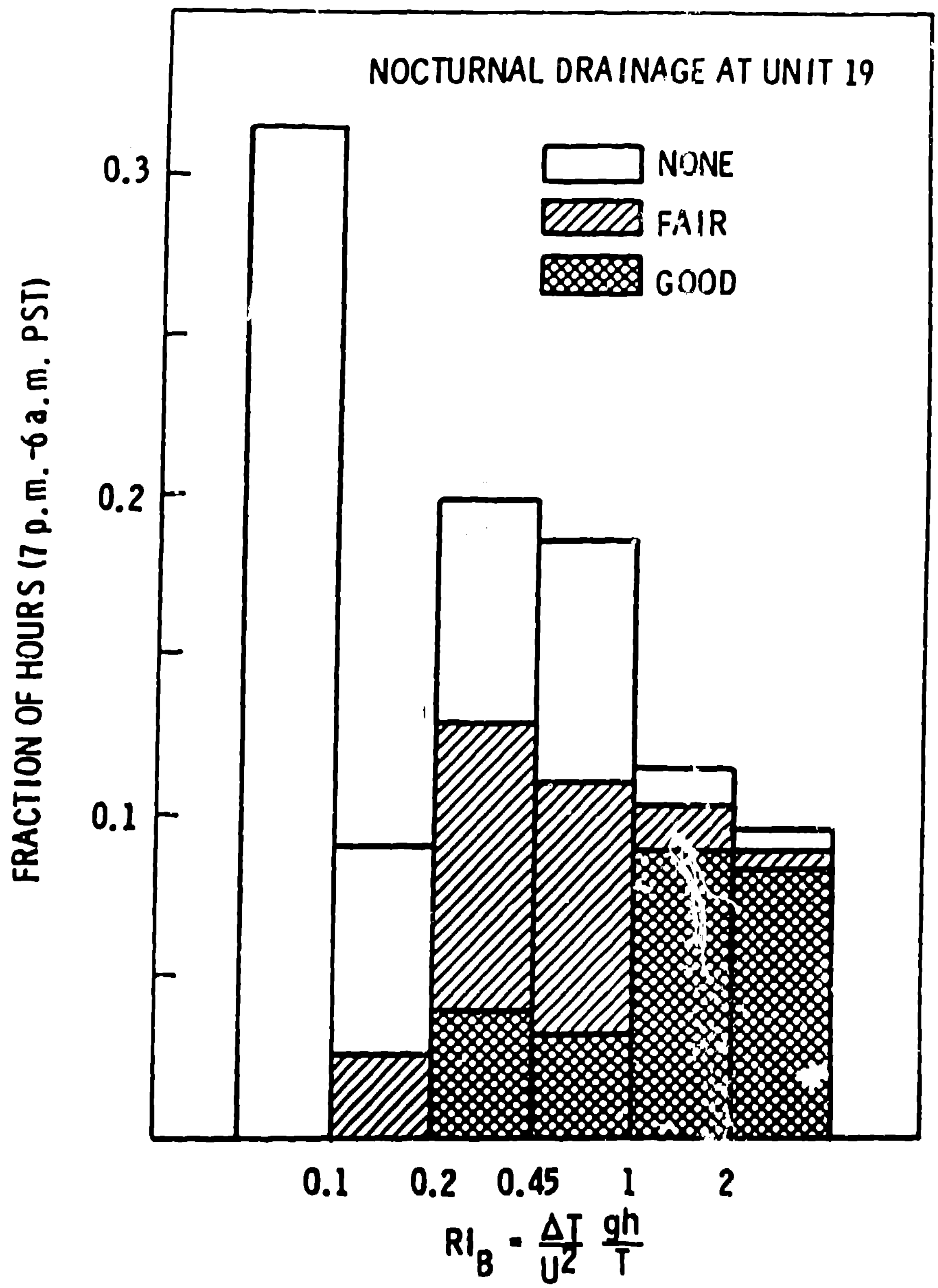

NOCTURNAL DRAINAGE AT UNIT 19
NONE
FAIR
GOOD
FRACTION OF HOURS (7 p.m. - 6 a.m. PST)
0.3
0.2
0.1
0.1
0.2
0.45
1
2
$RI_B = \frac{\Delta T}{U^2} \frac{gh}{T}$

FIG. 2

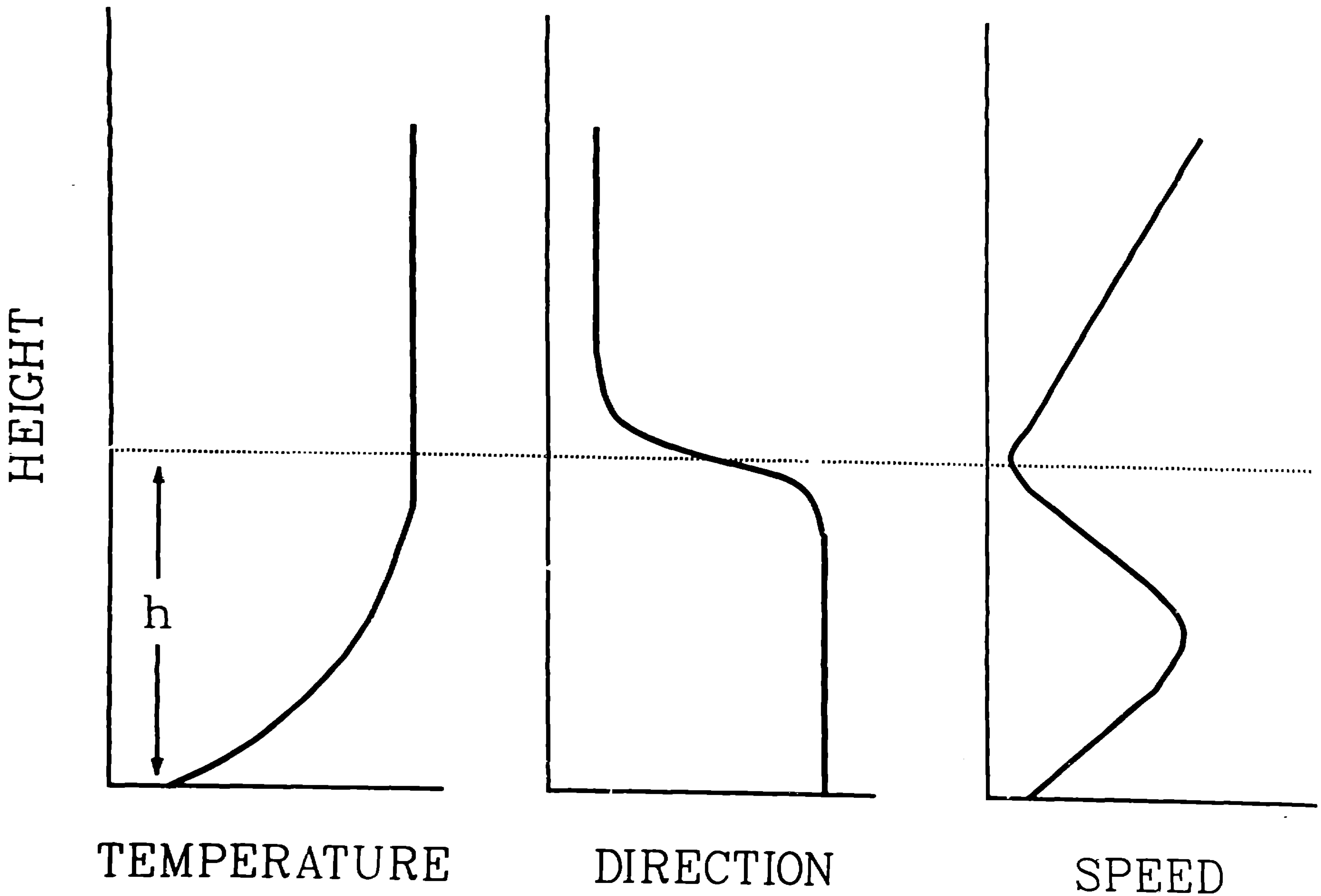


FIG. 3

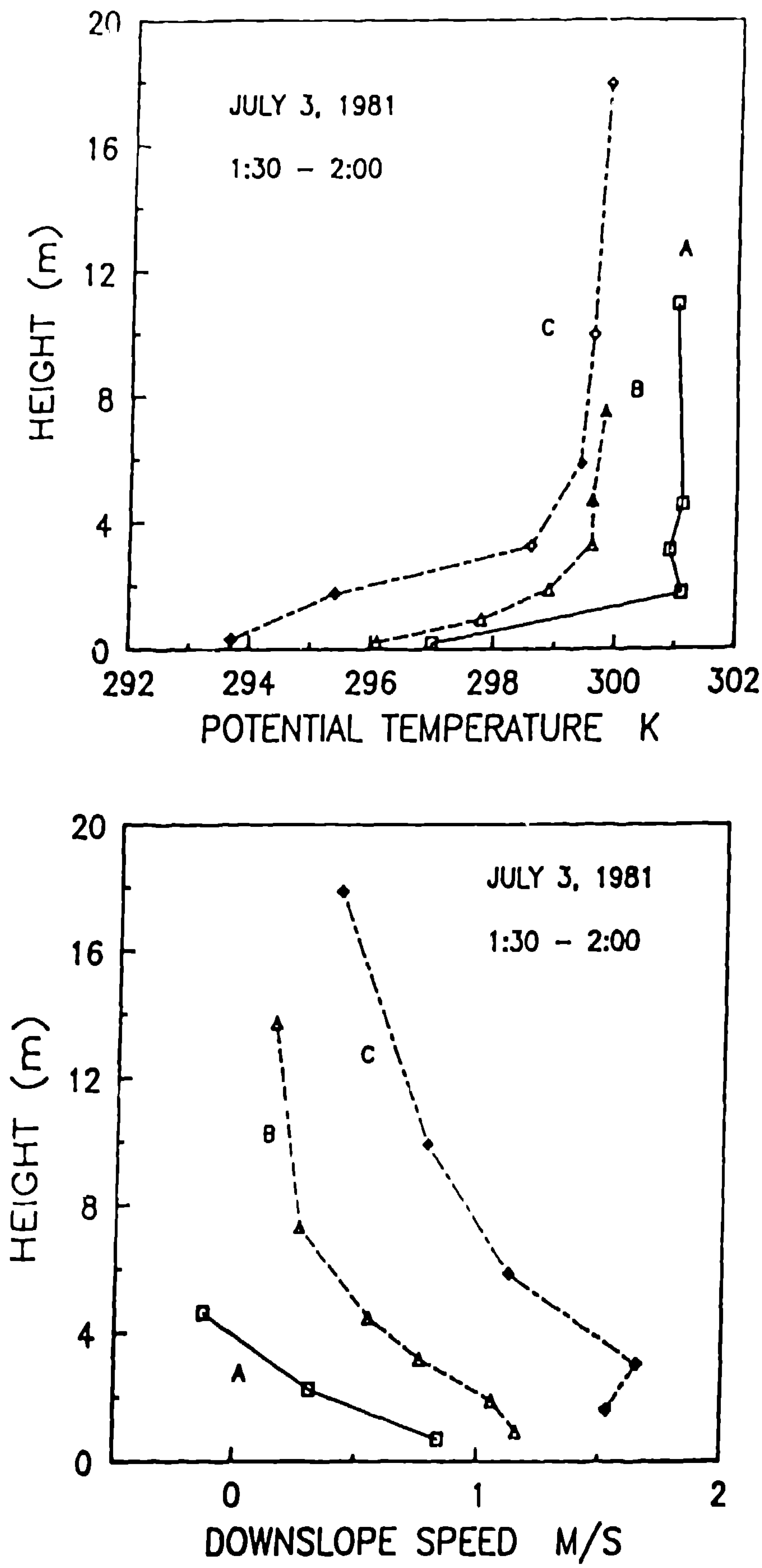
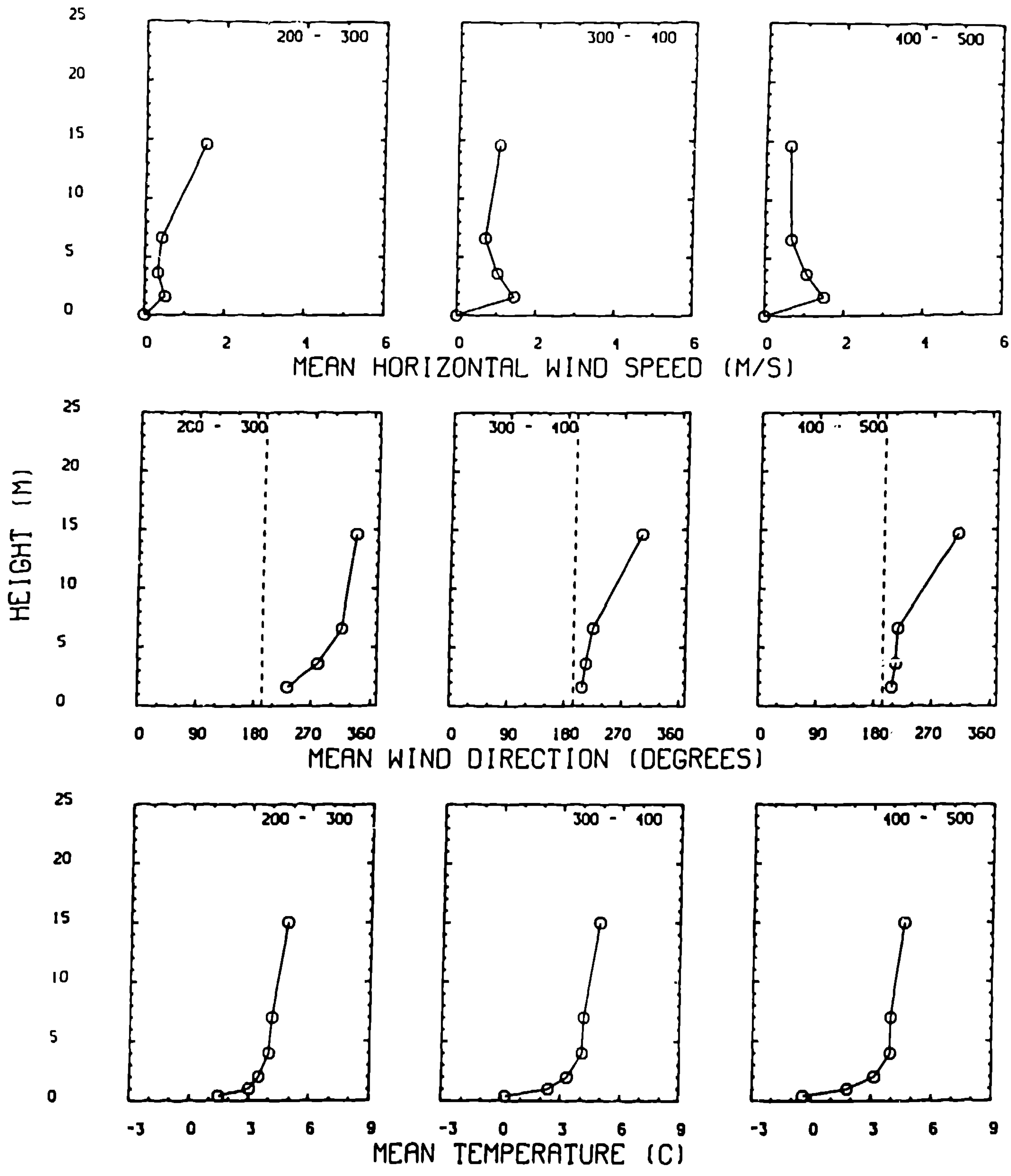

JULY 3, 1981
1:30 - 2:00
HEIGHT (m)
POTENTIAL TEMPERATURE K
A
B
C
JULY 3, 1981
1:30 - 2:00
HEIGHT (m)
DOWNSLOPE SPEED M/S
A
B
C

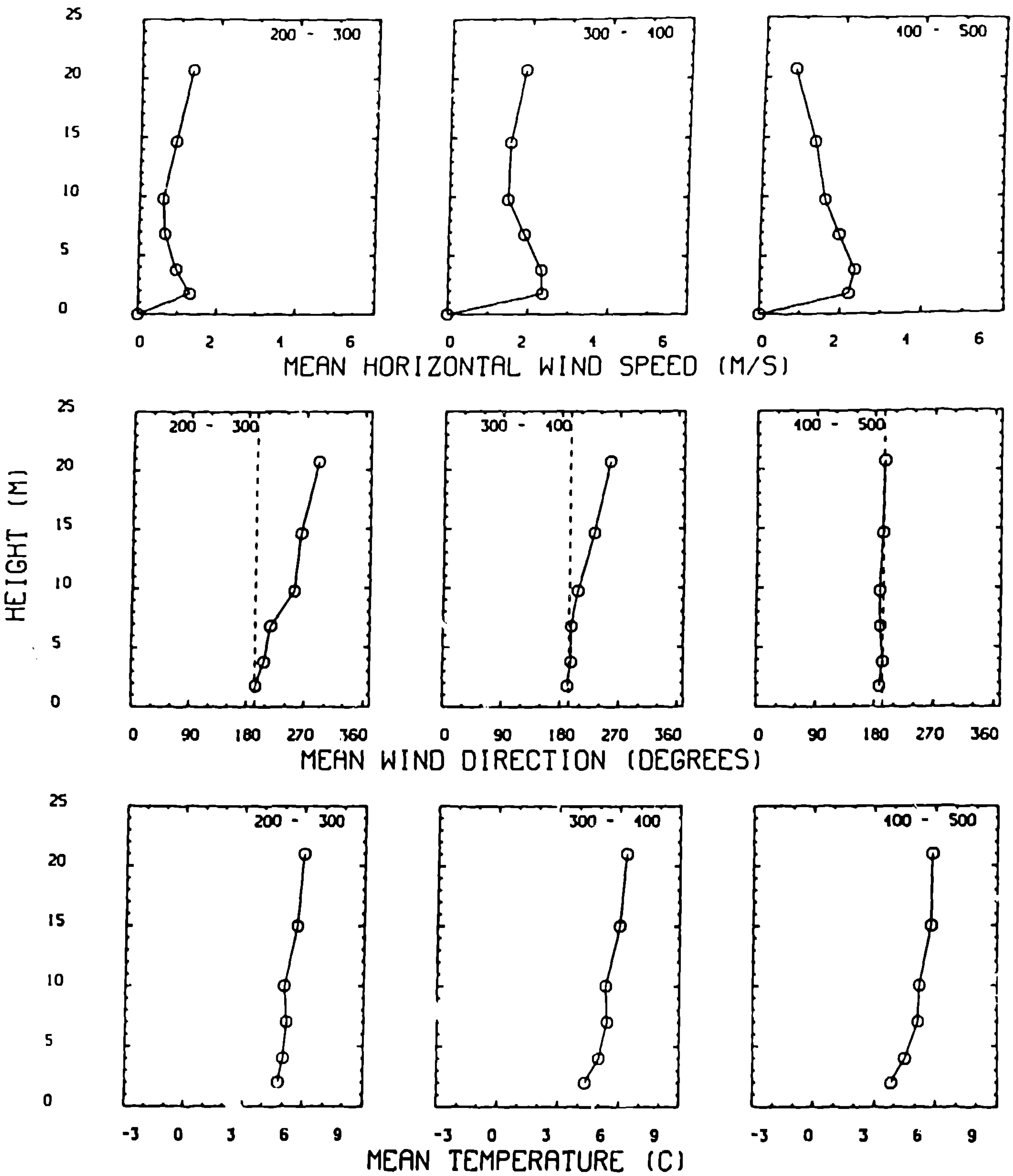
FIG. 4



STATION 2; JULIAN DAY 310
RADIATION SUNSET 1445 HOURS
RADIATION SUNRISE 930 HOURS

TOWER2

FIG. 5



STATION 1; JULIAN DAY 310
RADIATION SUNSET 1445 HOURS
RADIATION SUNRISE 930 HOURS

TOWER1

FIG. 6

CORRAL GULCH CO   TETHERSONDE FLT 29   DATE: 800810   0007 TO 0018 MST

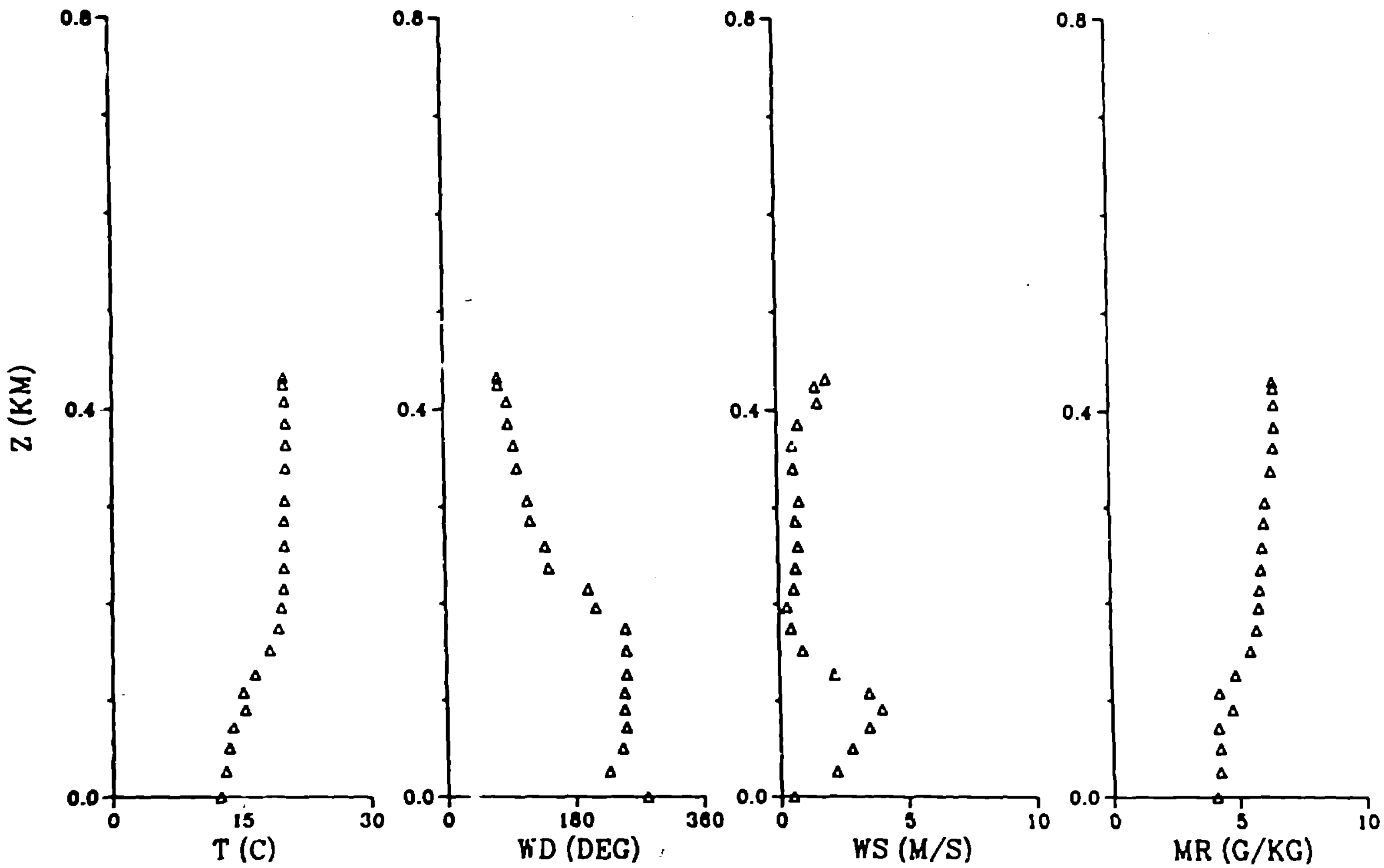


FIG. 7

Tethersonde (ATDL) at BRUSH CREEK
From 0500 MST to 550 MST on July 31, 1982
(From 600 to 650 MDT)

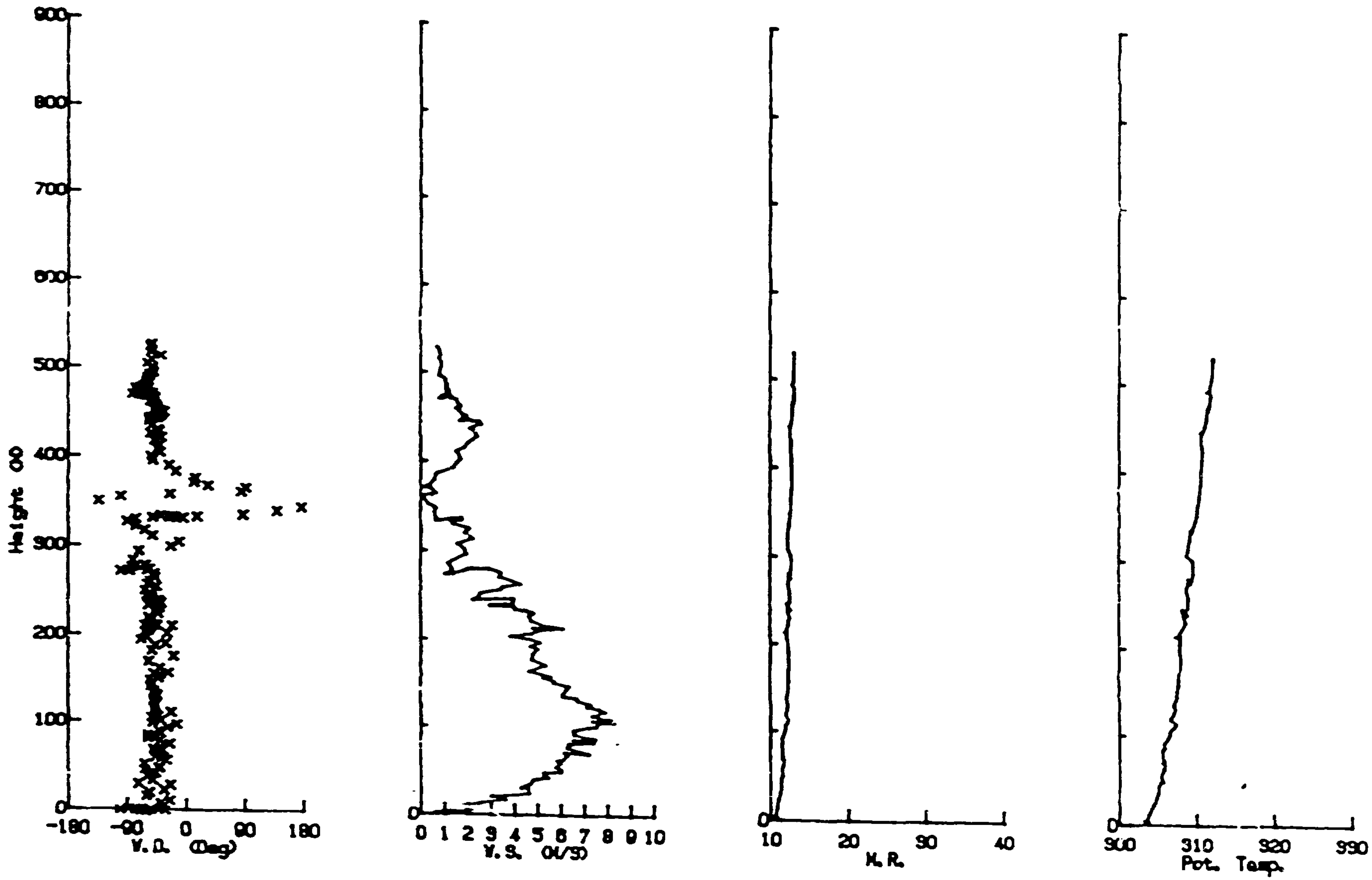


FIG. 8

GEYSERS 80 TETHERSONDE FLT 39 DATE: 800919 358 TO 414 PST

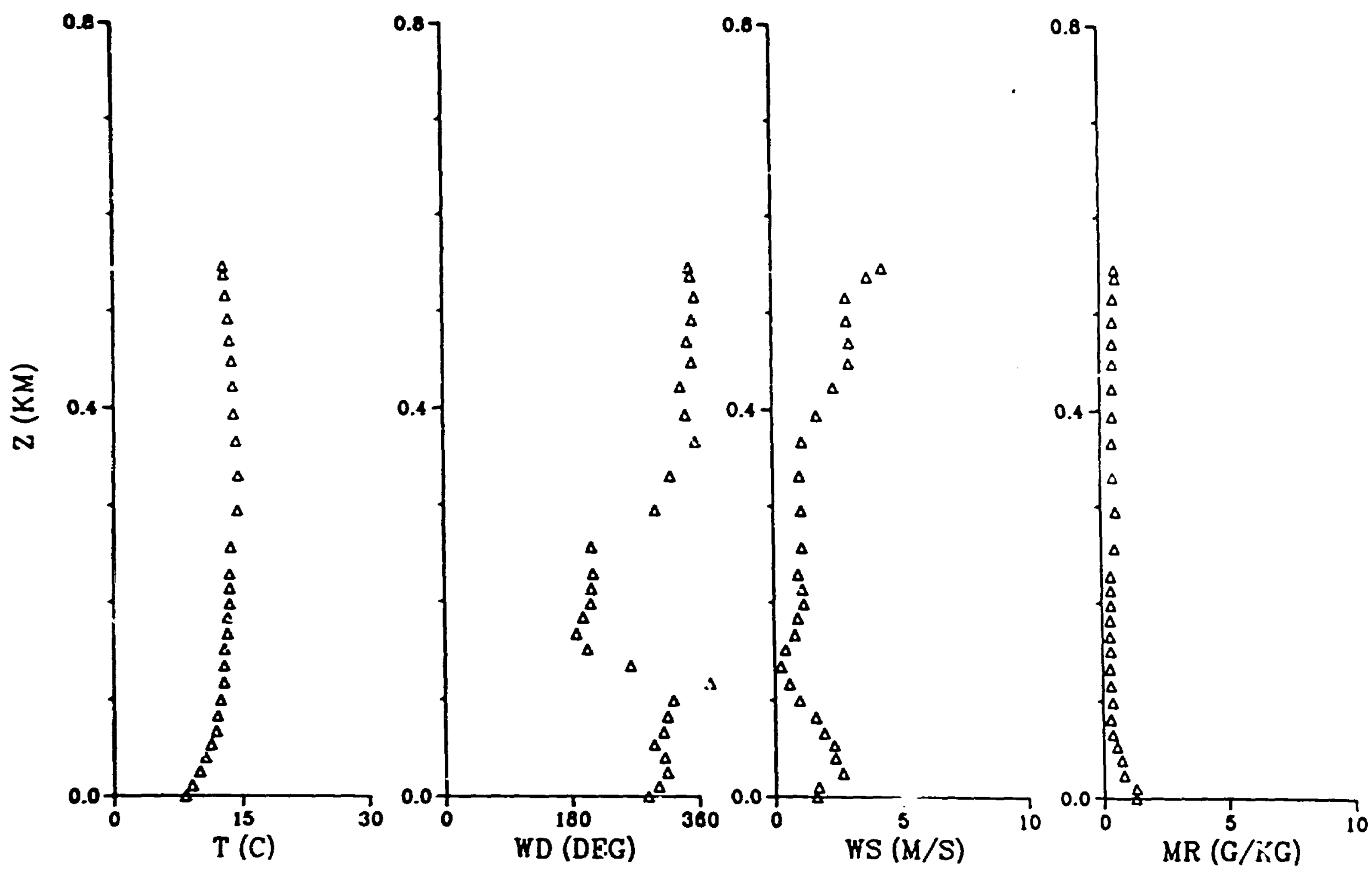


FIG. 9

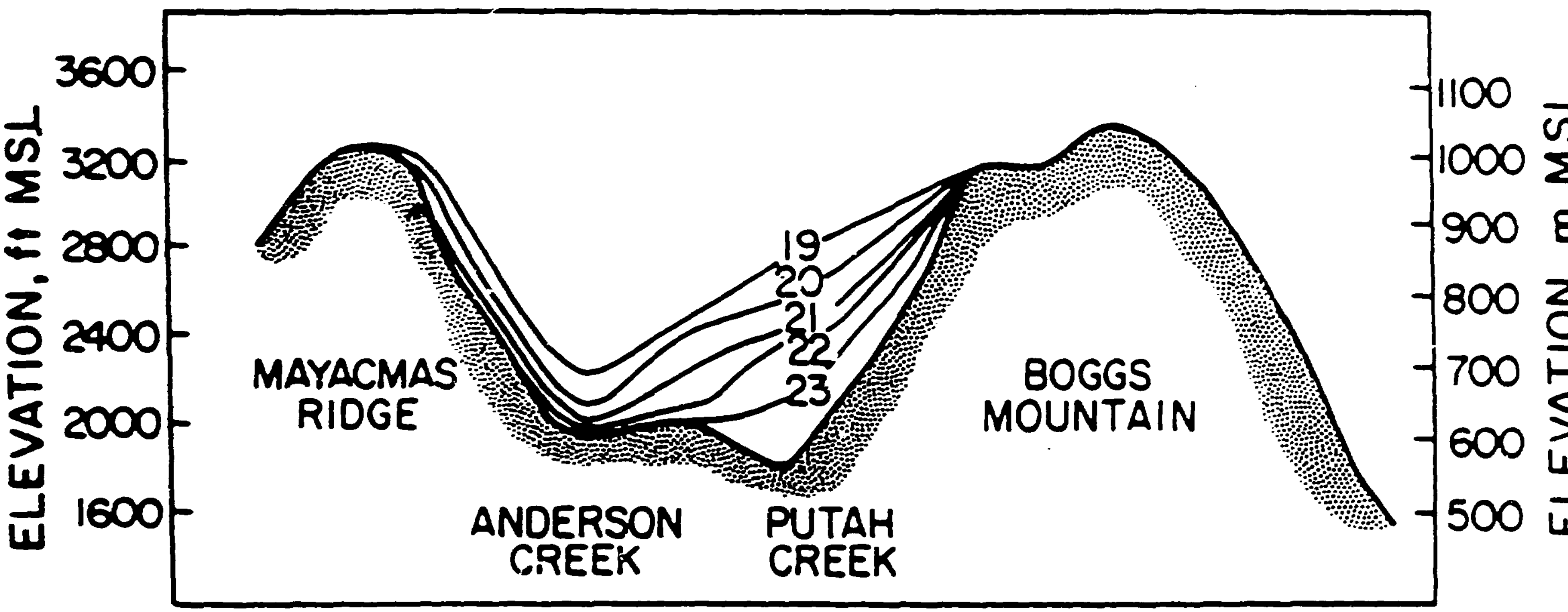

ELEVATION, ft MSL
3600
3200
2800
2400
2000
1600
ELEVATION, m MSL
1100
1000
900
800
700
600
500
MAYACMAS RIDGE
ANDERSON CREEK
PUTAH CREEK
BOGGS MOUNTAIN
19
20
21
22
23

FIG. 10

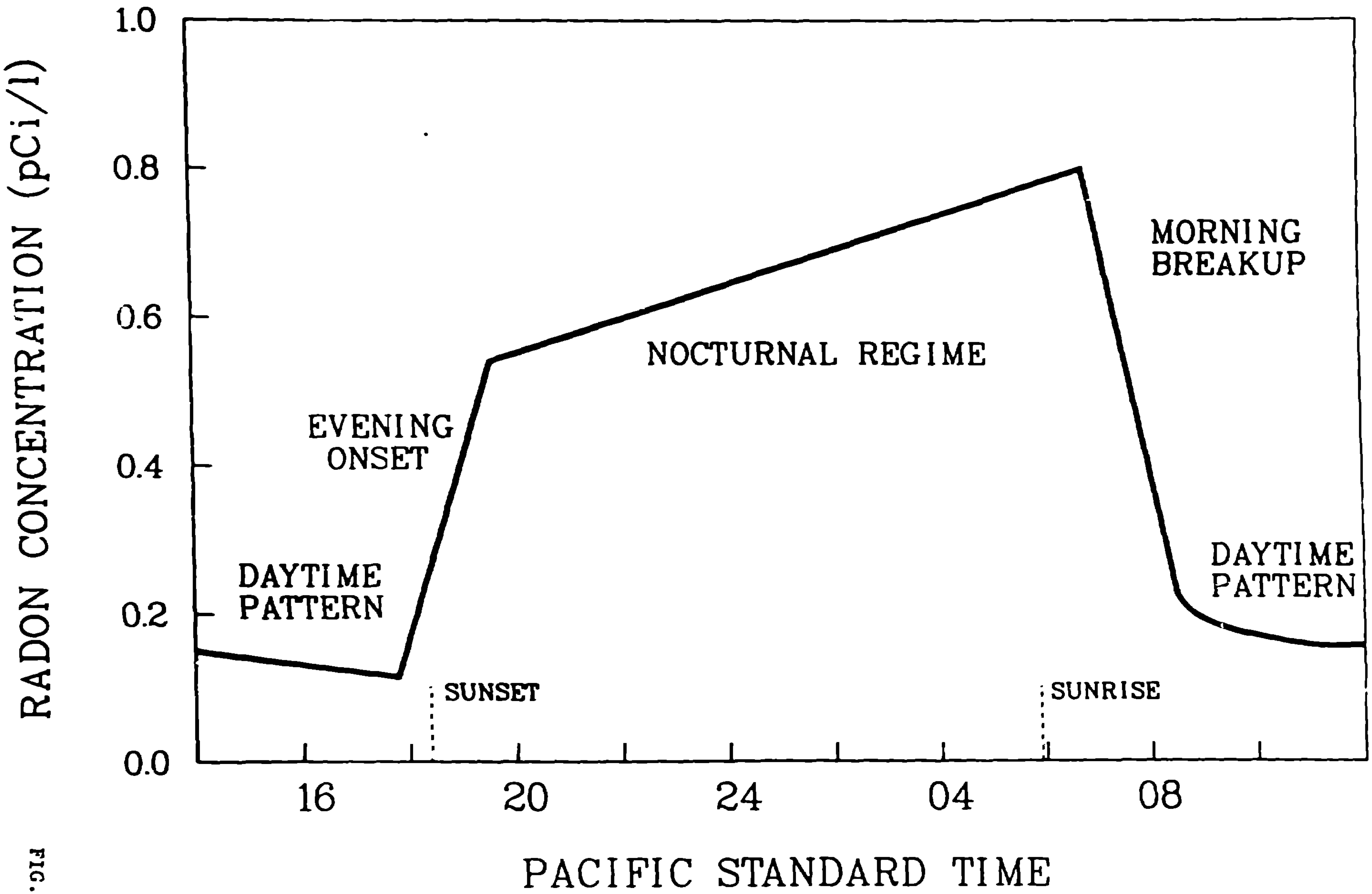

RADON CONCENTRATION (pCi/l)
1.0
0.8
0.6
0.4
0.2
0.0
DAYTIME PATTERN
EVENING ONSET
NOCTURNAL REGIME
MORNING BREAKUP
DAYTIME PATTERN
SUNSET
SUNRISE
16
20
24
04
08
PACIFIC STANDARD TIME

FIG. 11